UCRL-ID-133538

A Low-Noise Semiconductor Optical Amplifier

R.P. Ratowsky, S. Dijaili, J.S. Kallman, M.D. Feit, J. Walker

March 23, 1999

U.S. Department of Energy

Lawrence
Livermore
National
Laboratory

A Low-Noise Semiconductor Optical Amplifier

LDRD Final Report
Tracking Code 97-LW-014

R. P. Ratowsky, S. Dijaili, J. S. Kallman, M. D. Feit, and J. Walker

Introduction

Optical amplifiers are essential devices for optical networks, optical systems, and computer communications. These amplifiers compensate for the inevitable optical loss in long-distance propagation (>50 km) or splitting (>10×). Fiber amplifiers such as the erbium-doped fiber amplifier have revolutionized the fiber-optics industry and are enjoying widespread use. Semiconductor optical amplifiers (SOAs) are an alternative technology that complements the fiber amplifiers in cost and performance.

One obstacle to the widespread use of SOAs is the severity of the inevitable noise output resulting from amplified spontaneous emission (ASE). Spectral filtering is often used to reduce ASE noise, but this constrains the source spectrally, and improvement is typically limited to about 10 dB. The extra components also add cost and complexity to the final assembly. The goal of this project was to analyze, design, and take significant steps toward the realization of an innovative, low-noise SOA based on the concept of "distributed spatial filtering" (DSF).

In DSF, we alternate active SOA segments with passive free-space diffraction regions (see Fig. 1). Since spontaneous emission radiates equally in all directions, the free-space region lengthens the amplifier for a given length of gain region, narrowing the solid angle into which the spontaneous emission is amplified [1,2]. Our innovation is to use spatial filtering in a differential manner across many segments, thereby enhancing the effect when wave-optical effects are included [3]. The structure quickly and effectively strips the ASE into the higher-order modes, quenching the ASE gain relative to the signal.

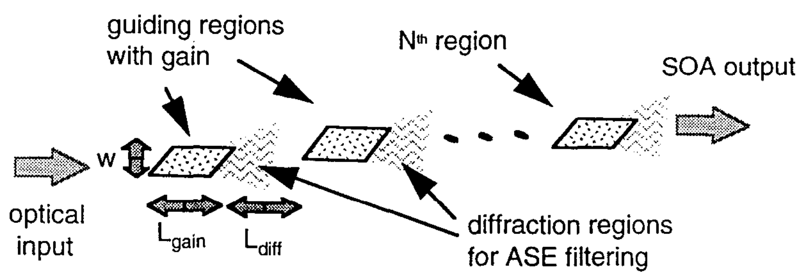

Figure 1. Geometry of the distributed spatial filter semiconductor optical amplifier (DSF-SOA)

Modeling and Design. An important aspect of this work was development of a computational model for the low-noise SOA. We enhanced BEEMER, a fast-Fourier-transform, beam-propagation-method code to include distributed spontaneous emission, gain saturation, and other SOA physics. BEEMER calculates ASE power by averaging the output over ensembles of randomly phased sources [4].

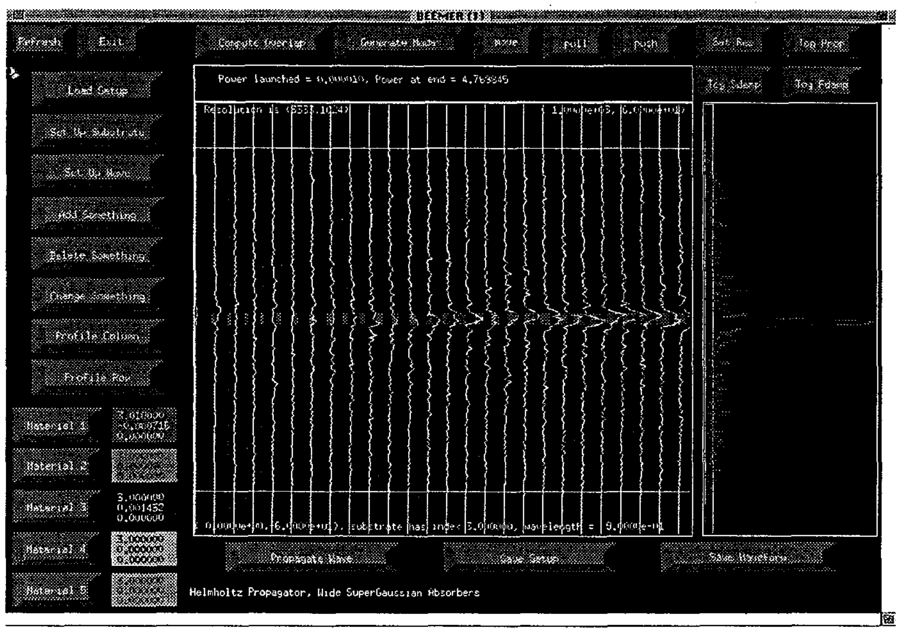

Figure 2. SOA Simulation is simplified with the BEEMER GUI

Figure 2 shows the BEEMER graphical user interface for a model of a 'chirped' SOA whose segments increase in size along the propagation direction. The red regions are the gain segments, and the blue regions are lossy regions which result from absorption in the unpumped areas of semiconductor. On the right-hand-side of the window the spontaneous emission noise intensity of the SOA is shown.

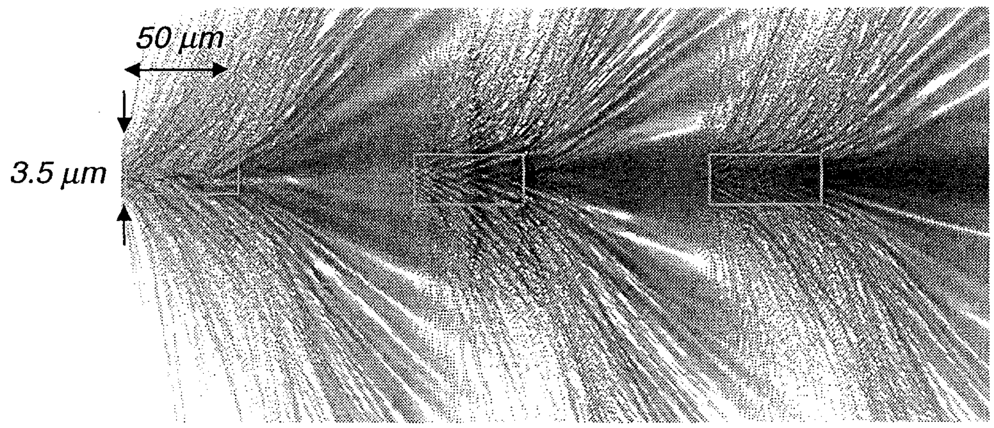

Figure 3. BEEMER simulation shows wide-angle diffraction of ASE in the free-space regions

Figure 3 shows the result of a SOA-BEEMER simulation where the diffraction of the ASE in the free-space regions is clearly visible. The yellow boxed regions are the gain segments where ASE occurs.

The most significant result of our modeling was a definitive calculation that confirmed the fundamental concept for the low-noise SOA: ASE gain is not equal to signal gain. As an example, consider the configuration shown in Fig. 4. If we calculate the ASE power as a function of device length (i.e., number of DSF segments). In figure 5 we have plotted the ASE and signal power against the number of SOA/free-space stages in a device; the slope of the curves is the gain. The signal power increases exponentially, but the ASE power clearly grows more slowly. The slope of the ASE curve is smaller in the middle of the plot, showing that the ASE gain is indeed smaller than signal gain. This SOA alternates 50-µm gain and free-space segments; the material gain is 100/cm.

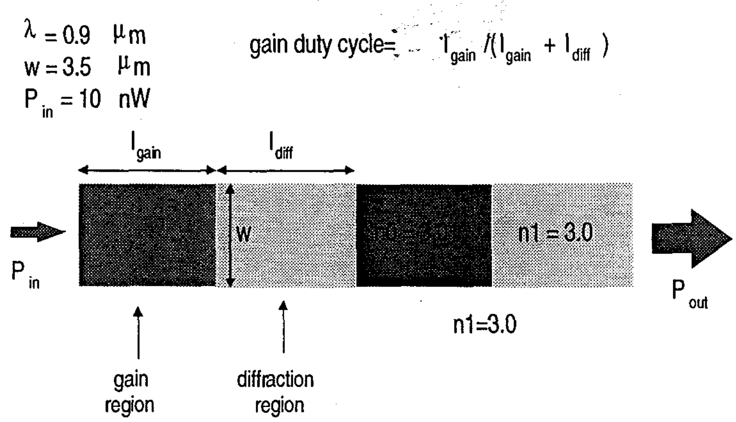

Figure 4. Simulation parameters and definitions

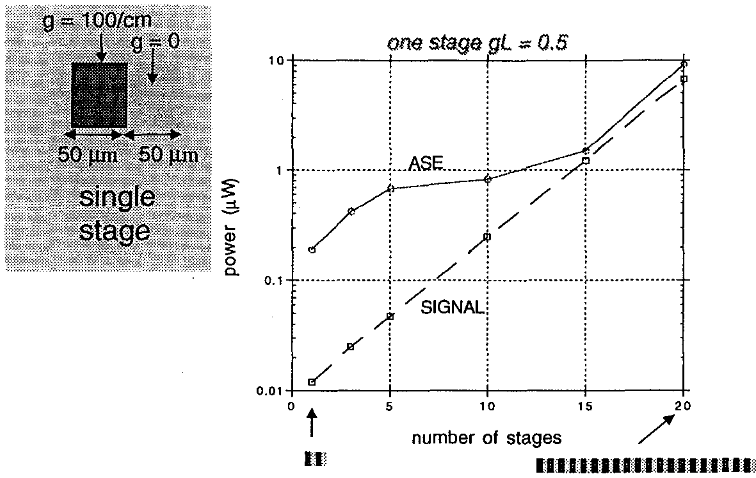

Figure 5. Variation of output power as the number of identical stages is increased, showing that ASE gain is not equal to signal gain

Because the multimode nature of the device (essential for DSF) is suppressed, the effect disappears for larger gain. This is evident in Fig. 5, where the gain of the ASE ultimately matches that of the signal for a large number of segments. If we increase the material gain to 150/cm, the effect disappears entirely, as shown in Fig. 6. We also observe Fig. 6 that at short device length the ASE gain is actually larger than the signal gain. This is the so-called 'excess noise' phenomenon, which results from the ASE initially having greater coupling to the highest gain mode of the device than the signal mode itself.

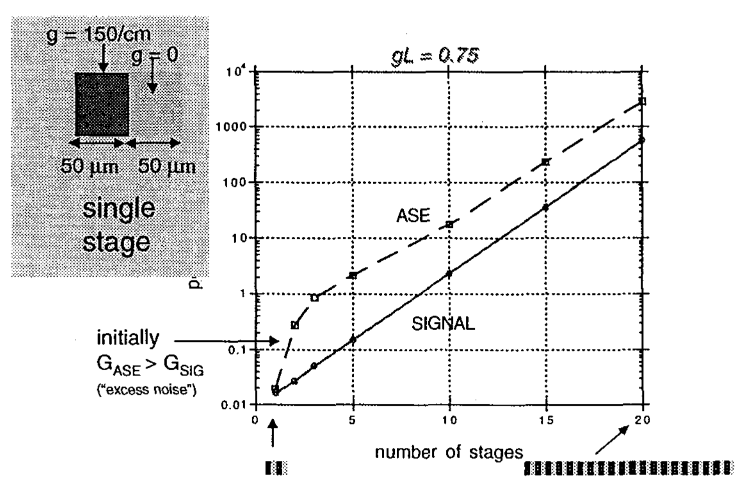

Figure 6. DSF is ineffective if the gain-length per stage is too large

An important design parameter for the low-noise SOA is the signal-to-noise ratio, which we show in Fig. 7 as a function of device length. As would be expected from the behavior shown in Fig. 5, the SNR increases up to an optimal device length, then saturates as the DSF effect is quenched by the high gain.

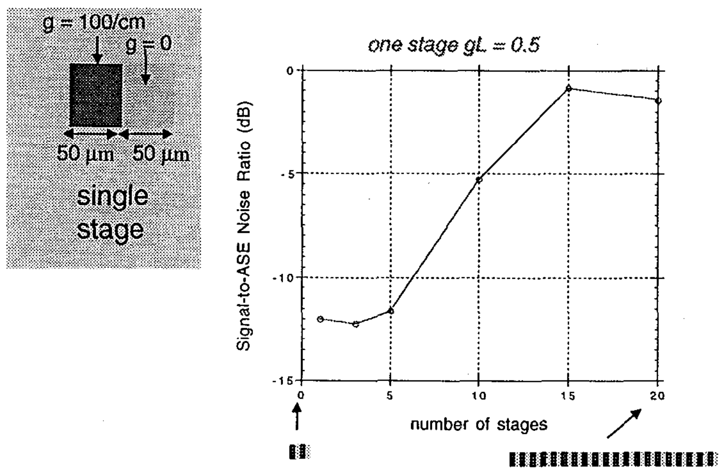

Figure 7. The signal-to-noise ratio grows exponentially as the number of identical stages is increased

If we compare the SNR for a DSF-SOA with that of conventional SOA having the same signal gain, we find that the SNR is significantly higher the DSF geometry. Figure 8 shows an example where the imporvement is better than 10 dB.

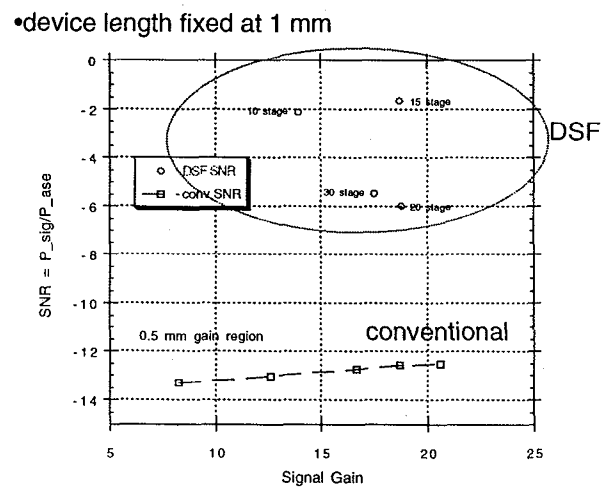

Figure 8 DSF gives better than 10 dB noise reduction over conventional SOA

Finally, we obtained an optimized design for a 1-mm DSF SOA device and showed that the signal-to-noise ratio peaks as the gain region duty cycle (the ratio of gain region to free-space region) is varied; this phenomenon is illustrated in Figure 9.

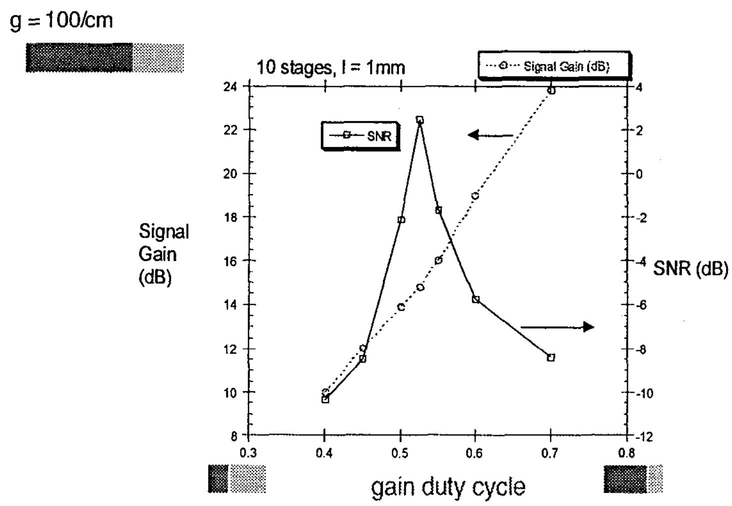

Figure 9 The SNR peaks sharply as gain duty cycle is increased

Experimental effort. In our experiments, we progressed toward the monolithic integration of and passive structures that is necessary for fabricating the DSF SOA structure.We found that $SiO_2/Ta_2O/SiO_2$ waveguides fabricated using magnetron sputtering had low propagation loss but high interface loss. We tried using an ion-beam sputtering technique, but then we were unable to achieve low propagation loss.

Because of reduced funding and loss of key personnel, we were unable ultimately to experimentally demonstrate the DSF SOA at the conclusion of the project. When the original P.I. left LLNL in November of 1997, the emphasis of the project shifted more to a theoretical and design effort which would point the way to fabrication with follow-on funding.

Publications

Ratowsky, R. P., S. Dijaili, J. S. Kallman, M. D. Feit, J. Walker, W. Goward, M. Lowry, "Modeling a distributed spatial filter low-noise semiconductor optical amplifier," *Integrated Photonics Research*, Victoria, BC, Canada, March 30-April 1, 1998 (conference), UCRL-JC-129108.

References.

[1] H. Kogelnik and A. Yariv, "Considerations of noise and schemes for its reduction in laser amplifiers", Proc. IEEE **52**, 165 (1964); A. Yariv, *Quantum Electronics*, John Wiley & Sons, New York, Chapter 21 (1989).
[2] A. E. Siegman, "Excess spontaneous emission in non-Hermitian optical systems. I. Laser amplifiers," Phys. Rev. A 39, 1253-1263 (1989).; I. H. Deutsch, J. C. Garrison and E. M. Wright, "Excess noise in gain-guided amplifiers", JOSA **B8**, 1244 (1991).
[3] S. P. Dijaili, F. G. Patterson, R. J. Deri, "Cross-talk free, low-noise optical amplifier, U. S. Patent Number 5,436,759 (1995).
[4] M. D. Feit and J. A. Fleck, "Wave-optics description of laboratory soft x-ray lasers", JOSA B7, 2048 (1990).